

## VPIC—Magnetic Reconnection

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**M**agnetic reconnection is a basic plasma process involving the rapid conversion of magnetic field energy into various forms of plasma kinetic energy, including high-speed flows, thermal heating, and highly energetic particles. These dynamical features are usually associated with changes in magnetic topology, which are conveniently viewed in terms of the breaking and reconnection of magnetic field lines. This process of *magnetic reconnection* is thought to play an important role in a diverse range of applications including solar flares, geomagnetic substorms, magnetic confinement fusion devices, and a wide variety of astrophysical problems.

In many applications, magnetic reconnection couples the large-scale plasma motion to fast dynamical processes at microscopic

scales. Many of the outstanding scientific challenges are related to this coupling between vastly different spatial and temporal scales.

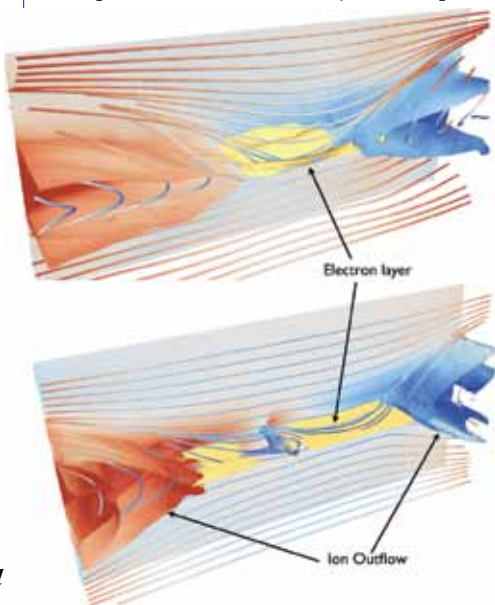
High-temperature plasmas are very good electrical conductors, which implies that the magnetic field is constrained to move together with the plasma. For reconnection to proceed, it is necessary to break

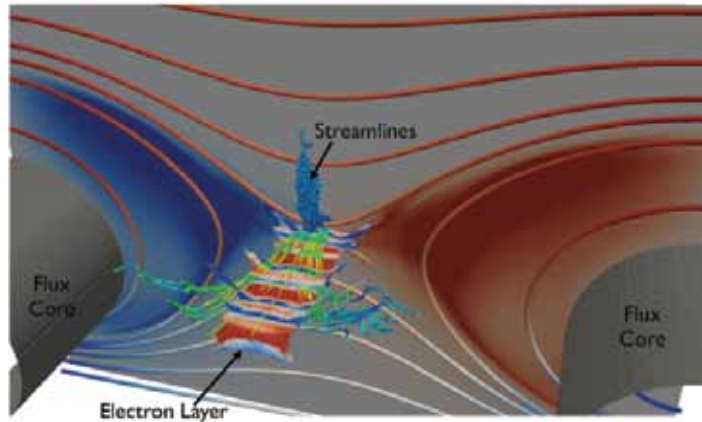
this constraint within so-called *diffusion regions*, which are quite small in comparison to the macroscopic scale but play a critical role in the evolution. Researchers are working to understand the basic physics of these regions, as well as the coupling to the larger system. Due to the complexity of the relevant nonlinear processes, simulations have played an important role in this scientific progress. Most previous studies have focused on 2D models using a variety of fluid and kinetic descriptions. With increasing computer power, these simulations have progressed to larger systems and raised new questions. In particular, recent 2D kinetic simulations have demonstrated that diffusion regions often form elongated current sheets that are unstable to various plasma instabilities [1]. Understanding the 3D evolution of these layers is a formidable challenge that requires petascale computing.

To address these questions, LANL scientists are utilizing the 3D kinetic plasma simulation code VPIC [2], which provides a first-principles description of the relevant physics. The focus is to better understand the role of plasma instabilities on the 3D evolution of reconnection layers in both space and laboratory plasmas. The simulations performed on Roadrunner were of unprecedented scale and complexity, using upwards of 4096 ranks, ~200 billion particles, and requiring careful attention to boundary conditions, collisional physics, and new diagnostics. Despite these complications, the simulations achieved a factor of ~3x speedup using the IBM Cell Broadband Engine (Cell BE) processor. Here, we highlight a few science results emerging from these efforts.

In space and astrophysical applications, reconnection typically occurs in collisionless regimes and forms structures on both ion and electron kinetic scales. Since the macroscopic scales are vastly larger, it is not possible to study the global evolution while simultaneously resolving these small scales. To make progress, it is necessary to reduce the scale separation by employing artificial ion to electron mass ratios in the range  $m_i/m_e \sim 100\text{--}300$ , and to focus on thin current layers, which are the preferred sites for the onset of reconnection. Open boundary conditions [1] were employed to allow reconnection to develop over longer times, effectively mimicking the dynamics of a larger system using relatively small

**Fig. 1. Open boundary simulations for neutral sheet geometry feature two types of secondary instabilities within the electron layer: an electromagnetic kink wave (top) and flux rope formation (bottom). The boundary conditions permit inflow of new plasma (the top and bottom) and outflow of reconnected plasma (left and right). The outflow jets are visualized with a particle density isosurface colored by ion outflow velocity, while the central electron current sheet (yellow) corresponds to an isosurface of electron current density. Sample magnetic field lines are colored by the magnitude of the magnetic field. Simulation was performed with mass ratio  $m_i/m_e = 300$ , using 4096 ranks, 245 million cells, and 147 billion particles.**





**Fig. 2.** Simulations were performed on Roadrunner with geometry and boundary conditions relevant to the MRX experiment [4,6] including the influence of weak Coulomb collisions [7]. The reconnection process is driven by reducing the currents inside the flux cores (grey cylinders), which pulls magnetic flux inward towards the cores. The resulting ion flow velocity is illustrated on the back cutting plane along with characteristic magnetic field lines. The central electron current sheet is illustrated with an isosurface of the current density, colored by a vertical component of the current density to show the plasma instability within the electron layer. Sample electron streamlines illustrate the electron flow from the upstream region through electron layer into the downstream region. This simulation was performed with mass ratio  $m_i/m_e = 300$  using 2880 ranks, 720 million cells, and 144 billion particles.

simulation domains. Several of these simulations focused on neutral sheets, where the initial magnetic field reverses sign across the current layer and goes to zero in the center. After the onset and initial evolution, the diffusion region features highly elongated electron scale layers that are unstable to several plasma instabilities. As illustrated in Fig. 1, these modes include an electromagnetic wave that leads to *kinking* of the electron layer, and a secondary reconnection instability that gives rise to flux rope formation. The kink wave is similar to recent predictions from kinetic theory [3], while the flux ropes are the 3D analogue of secondary islands previously reported in 2D simulations [1]. Although these processes are qualitatively similar to recent 3D electron-positron ( $m_i = m_e$ ) simulations [4], this is the first time they have been observed for the high mass ratio limit  $m_i/m_e = 300$  that is now feasible with

Roadrunner. These new results are of great interest from several perspectives. First, the kink wave can potentially give rise to a wave-induced dissipation, which may dramatically alter the reconnection process. In addition, the formation of flux ropes introduces a strong perturbation of the diffusion region topology, modifying both the size and internal structure. These modifications can influence the macroscopically important parameters, such as the rate of plasma flow into the layer.

Magnetic reconnection is also of great interest in laboratory experiments, which offer the capability to study the structure and dynamics in a controlled setting. Three-dimensional kinetic simulations may serve as a bridge to help extrapolate ideas that have been validated in the laboratory to regimes of direct relevance to space and astrophysical plasmas. The Magnetic Reconnection eXperiment (MRX) at the Princeton Plasma Physics Laboratory (PPPL) is one leading experiment that has reported detailed measurements of the diffusion region, including the kinetic structure of the electron layer [5]. Weak binary Coulomb collisions are necessary to properly describe these plasmas, but the applicability of fluid models is questionable. The kinetic approach within VPIC includes experimental boundary conditions appropriate to MRX [6] and a Monte Carlo treatment of the collisions [7]. On Roadrunner, a series of simulations were performed to examine the influence of collisionality and plasma instabilities on the structure of the diffusion region. An example 3D simulation in Fig. 2 illustrates an electromagnetic instability within the electron current layer. This instability has certain similarities

with the kink instability discussed in Fig. 1. Researchers at LANL are working with the scientists at PPPL to perform comparisons with these new simulation results. These validation efforts will focus on the geometry of the electron layer and the observed electromagnetic wave spectra.

Together with ongoing theoretical work, these efforts are expected to shed new light on the influence of plasma instabilities on magnetic reconnection.

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